

Cluster Membership Probability: Polarimetric Approach

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ABSTRACT

Interstellar polarimetric data of the six open clusters Hogg 15, NGC 6611, NGC 5606, NGC 6231, NGC 5749 and NGC 6250 have been used to estimate the membership probability for the stars within them. For proper-motion member stars, the membership probability estimated using the polarimetric data is in good agreement with the proper-motion cluster membership probability. However, for proper-motion non-member stars, the membership probability estimated by the polarimetric method is in total disagreement with the proper-motion cluster membership probability. The inconsistencies in the determined memberships may be because of the fundamental differences between the two methods of determination: one is based on stellar proper-motion in space and the other is based on selective extinction of the stellar output by the asymmetric aligned dust grains present in the interstellar medium. The results and analysis suggest that the scatter of the Stokes vectors $q(\%)$ and $u(\%)$ for the proper-motion member stars depends on the interstellar and intra-cluster differential reddening in the open cluster. It is found that this method could be used to estimate the cluster membership probability if we have additional polarimetric and photometric information for a star to identify it as a probable member/non-member of a particular cluster, such as the maximum wavelength value (λ_{max}), the unit weight error of the fit (σ_1), the dispersion in the polarimetric position angles ($\bar{\epsilon}$), reddening ($E(B - V)$) or the differential intra-cluster reddening ($\Delta E(B - V)$). This method could also be used to estimate the membership probability of known member stars having no membership probability as well as to resolve disagreements about membership among different proper-motion surveys (Dias *et al.* 2006, Baumgardt *et al.* 2000, Belikov *et al.* 1999, Tucholke *et al.* 1986, Berger 1982).

Key words: Open clusters: polarization - membership probability: individual (Hogg 15, NGC 6611, NGC 5606, NGC 6231, NGC 5749, NGC 6250)

1 INTRODUCTION

In studies of star clusters there are several interesting aspects to be understood, such as stellar evolution, galactic structure and evolution, and stellar dynamics. Compared to single stars, distant star clusters can be identified more easily and their age can be determined more reliably. Since their inception, studies of star clusters have focused on cluster membership.

Proper-motion studies on cluster membership have made very significant contributions to star cluster research. The basic goal of astrometric cluster membership studies is the production of a color-magnitude diagram of probable members with reduced field star contamination (Cudworth

1997). It is difficult to confirm or discount the membership of stars having peculiarities, *e.g.*, pre-main-sequence stars, super-giants, Cepheids or other variables (Cudworth 1997). Proper motions with standard errors of 4 to 7 mas yr^{-1} will convey membership information at magnitudes down to ~ 16 th magnitude (Zacharias *et al.* 2004). Moreover, such precision can be achieved with more than one image/plate at each epoch and an epoch difference of 10 to 15 years depending on the distance to the object when the telescope plate scale is ~ 10 arcsec mm^{-1} (Cudworth 1986, 1997). However, several disagreements about memberships among different proper-motion surveys have arisen (Dias *et al.* 2006, Baumgardt *et al.* 2000, Belikov *et al.* 1999, Tucholke *et al.* 1986, Berger 1982). To overcome the limitations of the current method, another robust method is required that is independent of the current method.

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Table 1. List of selected open clusters for analysis

Cluster Name (1)	$E(B - V)$ (in mag) (2)	Distance (in kpc) (3)	Age (in Myr.) (4)	Polarimetric data (5)	Proper-motion membership (6)
Hogg 15	1.16 ± 0.03	3.0 ± 0.3	6.0 ± 2	Orsatti <i>et al.</i> 1998	Dias <i>et al.</i> 2006
NGC 6611	0.85 ± 0.05	3.2 ± 0.3	3.0 ± 2	Orsatti <i>et al.</i> 2000	Belikov <i>et al.</i> 1999
NGC 5606	0.50 ± 0.05	2.4	6.0 ± 2	Orsatti <i>et al.</i> 2007	Dias <i>et al.</i> 2006
NGC 6231	0.46 ± 0.05	1.6 ± 0.05	4.0 ± 1	Feinstein <i>et al.</i> 2003	Dias <i>et al.</i> 2006
NGC 5749	0.42 ± 0.04	1.2 ± 0.18	27.0	Vergne <i>et al.</i> 2007	Dias <i>et al.</i> 2006
NGC 6250	0.33 ± 0.05	1.0	14.0	Feinstein <i>et al.</i> 2008	Dias <i>et al.</i> 2006

The light from distant stars is partially plane polarized, which is thought to be due to dust grains in the interstellar medium, which are also responsible for the reddening of starlight. According to the Davis and Greenstein mechanism, the polarization of starlight is caused by selective extinction due to asymmetric dust grains aligned in the interstellar medium, possibly by the galactic magnetic field (Davis *et al.* 1951). However, identifying the dominant grain alignment mechanism has proved to be an intriguing problem in grain dynamics (Lazarian *et al.* 1997). If the polarization is specifically produced by the dust grains present in the interstellar medium, then it will depend on distance as well as the generation method of the dust grains in that line of sight. Hence, the percentage of polarization and position angle along with the interstellar reddening may provide an independent measure of cluster membership probability under certain conditions (Feinstein *et al.* 2008, Vergne *et al.* 2007, Berger 1982). In this paper, the consistency tests, assumptions and validity of polarimetric cluster membership probability in comparison with proper-motion cluster membership probability will be explored using interstellar polarimetric data available for different open clusters. The rest of the paper is organized as follows. In Section 2 we present the concept of polarimetric cluster membership and selection of open clusters. The details of the procedures and method adopted for estimating polarimetric cluster membership probabilities are presented in Section 3. In Section 4 we present the scatter of the Stokes vectors in $q(\%)$ versus $u(\%)$ plots. In Section 5 we discuss intrinsic sources of polarization in stars. The polarimetric cluster membership probability for stars is presented in Section 6. In Section 7 we present a detailed study of the open cluster NGC 6231. Finally, a discussion is presented in Section 8, and we conclude with a summary in Section 9.

2 POLARIMETRIC CLUSTER MEMBERSHIP AND SELECTION OF OPEN CLUSTERS

In the past few years, interstellar polarization has been used to obtain the cluster membership probability for individual stars in different open clusters (Feinstein *et al.* 2008, Vergne *et al.* 2007, Berger 1982). The stellar output of individual stars of different clusters passing through a substantial amount of interstellar matter is subject to extinction and linear polarization. Both phenomena depend on the particle size distribution of the aligned dust grains and vary as a function of the product of the particle size distribution and the appropriate cross section for extinction and polarization. However, the polarization also depends on the frac-

tion of asymmetric dust grains of a particular size which are aligned by the galactic magnetic field. A correlation between these two phenomena cannot be obtained for all cases due to variations of the grain alignment efficiency. Entire populations of unaligned and unelongated grains may contribute to extinction but not to polarization. Ideally, the member stars of a particular cluster should show similar interstellar polarization and position angles because their light outputs encounter the same amount of dust grains and a homogeneous magnetic field, as they are located at nearly the same distance. It is expected that non-member stars will show different interstellar polarizations and position angles because they are located at different distances/lines of sight and their light outputs encounter different amounts and sizes of dust grains. However, this may not be true for all cases. If the distribution of dust grains and magnetic fields are not uniform inside a cluster and/or in a line of sight, then the member stars of a cluster would show different interstellar polarizations and position angles. Large scale changes in the dust grain distribution and magnetic field homogeneity in different parts of the line of sight may also cause depolarization of initially polarized light. Moreover, it is possible that some of the member stars may have an intrinsic source of linear polarization. In that case, the intrinsic component of polarization may enhance or depolarize the interstellar component of polarization of that particular star. To apply the method successfully to estimate the cluster membership probability based on interstellar polarization, the amount of interstellar selective extinction and polarization vector should be similar for all the member stars of a cluster.

To test the consistency of this technique we selected six open clusters for analysis based on the following criteria: (1) available interstellar polarization data, (2) existence of a proper-motion cluster membership probability and (3) all samples distributed over a wide coverage of reddening. The third criterion is set to check the dependency of polarization upon reddening. The open clusters Hogg 15, NGC 6611, NGC 5606, NGC 6231, NGC 5749 and NGC 5606 fulfill the above criteria with a the reddening coverage from 1.15 to 0.37. A brief description of the clusters follows and the important parameters of the clusters are given in Table 1.

The 6 ± 2 -Myr-old highly reddened open cluster Hogg 15 is located at a distance of 3 ± 0.3 kpc (Sagar *et al.* 2001). It is one of the few clusters known to lie in the second inner arm of our Galaxy. Hogg 15 is affected by non-uniform reddening across the cluster. The differential and average values of the reddening are nearly 0.20 mag and 1.16 ± 0.03 mag, respectively (Sagar *et al.* 2001, Moffat 1974). Orsatti

et al. 1998 have performed a multi-band polarimetric study on 23 stars in Hogg 15. Of these 23 stars, only 17 have an available proper-motion cluster membership probability (Dias *et al.* 2006). So, for analysis we have taken the polarimetric data from Orsatti *et al.* 1998 and the proper-motion cluster membership probability from Dias *et al.* 2006.

NGC 6611 is a very young open cluster located at a distance of 3.2 ± 0.30 kpc and embedded in an ionized hydrogen complex (M16) in the Sagittarius spiral arm (Winter *et al.* 1997, Sagar *et al.* 1979). The extinction law in the cluster NGC 6611 is variable. The value of extinction found by different observers varies from $R_V = 2.5 \pm 0.6$ to $R_V = 3.4 \pm 0.7$ (Turner 1994, Sagar *et al.* 1979, Gebel 1968, Johnson 1968). The average and differential values of reddening are nearly 0.85 ± 0.05 mag and 0.63 mag, respectively (Piatti *et al.* 2002, Sagar *et al.* 1979). IR studies concluded that the variable extinction in the north-west area of the cluster is caused either by circumstellar or intra-cluster dust (de Winter *et al.* 1997, Hillenbrand *et al.* 1993, Chini *et al.* 1983, Sagar *et al.* 1979). Orsatti *et al.* 2000 have performed a multi-band polarimetric study on 39 stars in this cluster. So, for analysis we have taken the polarimetric data from Orsatti *et al.* 2000 and the proper-motion cluster membership probability for all 39 stars from Belikov *et al.* 1999.

The 6 ± 2 -Myr-old open cluster NGC 5606 is located at a distance of 2.4 kpc (Piatti *et al.* 2002, Vazquez *et al.* 1991). The reddening across the cluster is variable. Differential and average values of reddening are nearly 0.32 mag and 0.50 ± 0.05 mag, respectively (Piatti *et al.* 2002, Vazquez *et al.* 1994). Orsatti *et al.* 2007 have made multi-band polarimetric observations on 54 stars in the direction of NGC 5606. Of these 54 stars only 20 have an available proper-motion cluster membership probability. So, for analysis, we have taken the polarimetric data from Orsatti *et al.* 2007 and the proper-motion cluster membership probability from Dias *et al.* 2006.

NGC 6231 is a young open cluster located in the core of the Sco OB1 association at a distance of 1.6 ± 0.05 kpc. The age of the cluster is nearly 4 ± 1 Myr (Sana *et al.* 2007, Piatti *et al.* 2002). The average reddening of the cluster is 0.46 ± 0.05 mag and it is variable inside the cluster (Sung *et al.* 1998). The value of differential reddening across the cluster is nearly 0.28 mag (Feinstein *et al.* 1968). Feinstein *et al.* 2003 have performed a multi-band polarimetric study on 35 stars in the cluster. In this paper we use the polarimetric data from Feinstein *et al.* 2003 and the proper-motion cluster membership probability for all 35 stars from Dias *et al.* 2006.

The 27-Myr-old, poorly populated open cluster NGC 5749 lies near the south-western edge of the Lupus constellation and is located at a distance of 1.28 ± 1.18 kpc (Claria *et al.* 1992). The average reddening of the cluster is nearly 0.42 ± 0.04 mag (Claria *et al.* 1992). The reddening across the cluster is variable and the value of differential reddening is nearly 0.13 mag (Claria *et al.* 1992). Vergne *et al.* 2007 have performed multi-band polarimetric observations on 31 comparatively bright stars in the cluster NGC 5749. Of these 31 stars, only 15 have an available proper-motion cluster membership probability. So, for analysis, we have taken the polarimetric data from Vergne *et al.* 2007 and the proper-motion cluster membership probability from Dias *et al.* 2006.

The open cluster NGC 6250 lies at the boundary of the next inner spiral (Sag-Car) feature and is located at a distance of 1.0 kpc (Bayer *et al.* 2000). It is effected by differential reddening across the cluster and the values of differential and average reddening are nearly 0.28 mag and 0.33 ± 0.05 mag, respectively (Bayer *et al.* 2000, Herbst 1977). The estimated age of the cluster is nearly 14 Myr (Bayer *et al.* 2000). Feinstein *et al.* 2008 have performed a multi-band polarimetric study on 32 stars in this cluster. Of these 32 stars 29 have a proper-motion cluster membership probability. So, for analysis the polarimetric data and the proper-motion cluster membership probabilities are taken from Feinstein *et al.* 2008 and Dias *et al.* 2006, respectively.

3 ESTIMATION OF THE POLARIMETRIC CLUSTER MEMBERSHIP PROBABILITY

The proper-motion cluster membership probability can be used as a reference for a consistency test of the polarimetric cluster membership probability. The stars of the different clusters were divided into four groups based on the proper-motion cluster membership probabilities, *viz.*, (1) proper-motion members with very high cluster membership probability, i.e. , $\geq 80\%$, (2) proper-motion members with a cluster membership probability between 50% and 80%, (3) proper-motion non-members with a cluster membership probability $< 50\%$ and (4) proper-motion non-members with very low cluster membership probability, i.e. , $< 20\%$ (Baumgardt *et al.* 2000, Berger 1982).

The cluster membership probability (Mp_{pol}^p) is estimated from the average deviation of the Stokes vectors q and u of an individual star from the mean values of q and u of the proper-motion group-one stars (groups of stars with very high proper-motion membership probability $> 80\%$). We may consider the proper-motion group-one stars as representative of a particular cluster because they have a very high membership probability. Percentage scaling/calibration of Mp_{pol}^p is performed using the full ranges (difference between maximum and minimum) of the Stokes vectors q and u , considering the same scale of 100% cluster membership probability. So, to estimate any individual star's cluster membership probability we compare the average deviation of the Stokes vectors with these ranges. The ranges of q and u are determined as being between the proper-motion group-one and group-four stars.

However, it is not possible to apply the same technique in a cluster where the proper-motion cluster membership probability for individual stars is not available. Keeping this in mind, we introduce another polarimetric cluster membership probability (Mp_{pol}^a), which can be easily estimated without prior proper-motion cluster membership information. The new cluster membership probability Mp_{pol}^a is estimated in a similar way as for Mp_{pol}^p , but the mean values and ranges of the Stokes vectors q and u are calculated considering all the stars available in a particular cluster.

4 SCATTER OF STOKES VECTORS

In cluster membership studies we consider a star to be a member of a particular cluster if the cluster membership

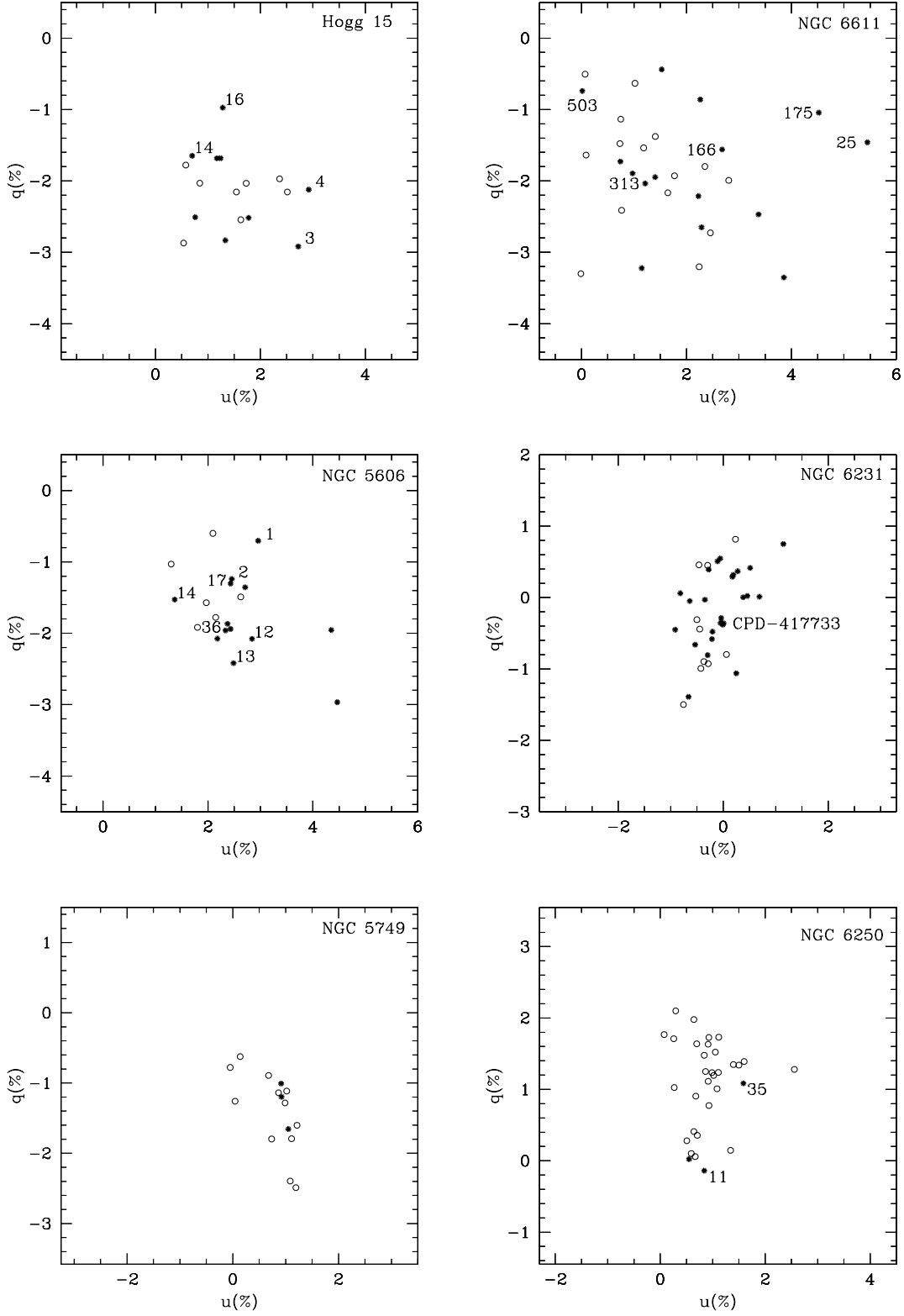


Figure 1. Polarization Stokes vectors $u(\%)$ and $q(\%)$ for stars with an available proper-motion cluster membership probability. Proper-motion cluster members are shown by filled-circle and non-members by open-circle symbols. The same range of X ($u(\%)$) and Y ($q(\%)$) scales are used in all the plots to visualize and compare the scatter in the different clusters.

Table 2. Reddening and scatter of the clusters

Cluster (1)	$E(B - V)$ (2)	$\Delta E(B - V)$ (3)	$Scatt_b$ (4)	$Scatt_a$ (5)
Hogg 15	1.16 ± 0.03	0.20	1.02 ± 0.34	0.64 ± 0.28
NGC 6611	0.85 ± 0.05	0.63	1.74 ± 0.44	1.39 ± 0.43
NGC 5606	0.50 ± 0.05	0.32	1.02 ± 0.28	1.16 ± 0.47
NGC 6231	0.46 ± 0.05	0.28	0.72 ± 0.14	0.73 ± 0.14
NGC 5749	0.42 ± 0.04	0.13	0.34 ± 0.19	0.34 ± 0.19
NGC 6250	0.33 ± 0.05	0.28	0.85 ± 0.49	—

probability is $> 50\%$, and consider it a non-member star otherwise. To present the difference in polarization between proper-motion member and non-member stars, we plot the Stokes vectors $u(\%)$ and $q(\%)$ for all six open clusters in Figure 1, in decreasing order of reddening. The filled circles represent the proper-motion member stars and the open circles represent the proper-motion non-member stars.

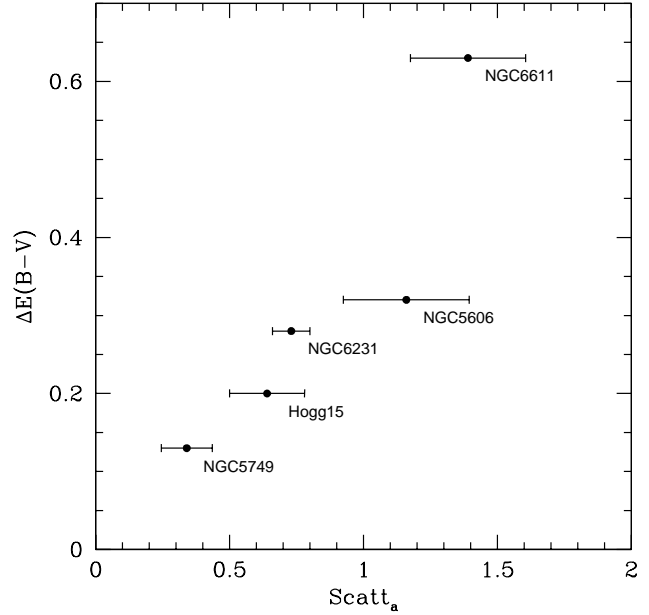
In Section 2, it was stated that the member stars of a particular cluster should show similar interstellar polarization and position angle if their light outputs encounter the same amount of dust grains and homogeneous magnetic field, and they are all located at nearly the same distances. If all the member stars satisfy these conditions then we could expect to observe a clustering of all the member stars in a $u(\%)$ versus $q(\%)$ plot.

We could easily infer from Figure 1 that the clustering of the member stars is very low in NGC 6611 while it is high in NGC 5749, compared with other clusters, or that the scatter of the member stars is very high in NGC 6611 and low in NGC 5749. However, by visual inspection it is very difficult to quantify the scatter of the member stars in the different clusters. Therefore, we have estimated the scatter ($Scatt_b$) and respective errors of the member stars in the different clusters, listed in the fourth column of Table 2. $Scatt_b$ is estimated from the square root of the sum of the squares of the Stokes vectors' standard deviations. It is clear from $Scatt_b$ and Fig. 1 that the scatter of the member stars in Hogg 15, NGC 6611 and NGC 5606 is high compared to that in NGC 6231, NGC 5749 and NGC 6250. In the case of clusters NGC 6611, NGC 5606, NGC 6231 and NGC 5749, it is also found that $Scatt_b$ follows the cluster's average reddening, i.e., the scatter is high towards higher reddening and vice versa. But, the clusters Hogg 15 and NGC 6250 do not follow the trend of reddening and scatter followed by the other four clusters. Further investigation is necessary for make a more precise conclusion.

5 STARS HAVING SOURCES OF INTRINSIC POLARIZATION

It has already discussed in Section 2 that our method is based on interstellar polarization data, which are extrinsic in nature and not variable in time. However, there is a chance that some stars in our sample may be sources of intrinsic polarization. Hence, we have to exclude all those stars from our sample which are sources of intrinsic polarization or produce variable polarization, *e.g.*, young stellar objects, variable stars etc.

In the cluster Hogg 15, the proper-motion cluster mem-

**Figure 2.** Scatter ($Scatt_a$) versus differential intra-cluster reddening ($\Delta E(B - V)$) plot for different clusters

bership probability and polarization data are available for 17 stars, and 9 of them have proper-motion cluster membership probabilities greater than 50%. According to the polarimetric study by Orsatti *et al.* 1998, the proper-motion member stars #14 and #3 (HD 311884) are both probable sources of intrinsic polarization (Feinstein *et al.* 1971). The Wolf-Rayet star HD 311884 is a short-period binary with strongly variable polarization, modulated by the stellar orbits (Moffat *et al.* 1990). The proper-motion member stars #16 and #4 are both variable in nature, one being a T-Tauri star and other a Wolf-Rayet star (Moffat 1974).

The proper-motion cluster membership probability and polarization data are available for 39 stars in the cluster NGC 6611 and only 15 of them have proper-motion cluster membership probabilities greater than 50%. According to Martayan *et al.* 2008, the proper-motion member stars #175, #313 and #25 are binary in nature, and #503 is a pre-main sequence star. The polarimetric study of the cluster NGC 6611 reveals that the member star #166 is a source of intrinsic polarization (Orsatti *et al.* 2000).

In the cluster NGC 5606, 19 stars have an available proper-motion cluster membership probability and polarimetric data, and 13 of them have proper-motion cluster membership probabilities greater than 50%. According to the polarimetric study of the cluster NGC 5606, the proper-motion member stars #1, #2, #12, #13, #14, #17 and #36 are probable sources of intrinsic polarization (Orsatti *et al.* 2007).

The proper-motion cluster membership probability and polarimetric data are available for 35 stars in the cluster NGC 6231, and 25 of them have proper-motion membership probabilities greater than 50%. The proper-motion member star #CPD-417733 is a short-period binary (Sana *et al.* 2008). The polarimetric study of the cluster NGC 6231 reveals that the proper-motion non-member stars #70, #73,

Table 3. Membership probability for the stars in the sample

ID (1)	$E(B - V)$ (mag) (2)	$M_{p_{prop}}$ (%) (3)	$M_{p_{pol}^P}$ (%) (4)	$M_{p_{pol}^a}$ (%) (5)
Hogg 15				
05	1.24	81	66	75
08	1.42	81	68	69
10	1.19	86	70	80
17	0.67	82	71	71
23	1.05	68	60	74
02	1.12	47	74	83
06	1.13	0	72	76
11	0.00	0	51	58
15	1.33	0	81	81
19	1.09	14	94	91
20	1.09	0	58	66
21	1.25	24	55	62
22	0.99	29	35	54
NGC 6611				
150	0.76	88	90	94
166	0.88	98	76	82
175	1.16	97	75	76
223	0.85	80	77	79
313	0.72	89	90	94
351	0.71	91	75	76
411	0.10	88	79	84
503	0.80	81	51	61
025	—	53	53	55
231	1.01	62	55	59
307	—	60	67	74
343	1.11	72	86	86
367	0.54	69	85	89
371	—	58	63	70
444	1.06	79	84	84
197	0.77	3	70	77
205	0.79	40	79	85
254	0.73	44	93	96
259	1.00	8	76	76
275	0.72	12	86	86
280	0.73	23	83	88
296	—	3	61	68
297	0.92	23	83	83
301	0.95	7	97	98
311	0.76	26	84	89
349	0.52	30	74	80
374	0.56	4	80	85
388	—	1	67	74
401	0.71	25	60	64
402	—	28	48	57
NGC 5606				
01	0.58	80	66	72
02	0.56	79	69	89
06	0.53	64	75	89
09	0.50	84	63	43
12	0.52	60	83	87
13	0.35	73	71	85
14	0.49	51	58	58
15	0.57	79	80	74
17	0.52	76	70	70
21	—	83	81	95
36	0.54	63	78	92
57	—	84	86	86
60	0.48	55	73	67
07	0.51	37	70	84

Table 4. Continuation of table 3

ID (1)	$E(B - V)$ (mag) (2)	$M_{p_{prop}}$ (%) (3)	$M_{p_{pol}^P}$ (%) (4)	$M_{p_{pol}^a}$ (%) (5)
NGC 5606				
10	0.49	16	50	70
20	—	01	77	94
24	—	04	46	67
58	0.54	15	68	89
59	0.43	30	75	93
NGC 6231				
001	0.45	90	82	84
006	0.45	85	88	89
034	0.46	81	68	74
105	0.56	84	84	89
110	0.52	86	94	91
112	0.50	88	94	95
161	0.51	91	75	77
166	0.51	87	69	71
184	0.46	82	97	96
189	0.45	83	87	89
194	0.46	90	95	96
224	0.52	88	92	90
232	0.52	88	89	93
238	0.47	84	93	91
248	0.47	88	66	71
259	0.45	92	86	89
261	0.46	90	92	93
266	0.44	89	77	78
272	0.41	87	88	89
286	0.43	91	78	80
289	0.43	89	71	73
CPD417733	—	91	94	90
016	—	52	89	90
080	0.60	63	72	75
287	0.45	58	66	69
070	0.54	0	61	67
073	0.64	0	81	86
102	0.45	0	90	94
220	0.47	0	85	86
253	0.46	23	86	91
254	0.47	0	95	97
290	0.53	0	85	86
HD152233	—	0	89	90
HD152235	—	0	85	89
HD152248	—	0	80	82
NGC 5749				
15	—	53	84	83
46	—	57	94	87
72	—	53	88	82
22	—	44	70	89
23	—	31	77	78
25	—	14	57	62
26	—	49	53	66
28	—	43	99	87
39	—	14	36	53
40	—	21	72	81
31	—	2	48	55
82	—	3	37	53
75	—	27	92	81
77	—	49	76	77
38	—	46	90	88

#220 and #254 are probable sources of intrinsic polarization (Feinstein *et al.* 2003).

Only 15 stars have an available proper-motion cluster membership probability and polarimetric data in the cluster NGC 5749 (Vergne *et al.* 2007, Dias *et al.* 2006). Of the 15 stars, only 3 have proper-motion membership probabilities greater than 50%. The proper-motion non-member star #75 is a probable source of intrinsic polarization (Vergne *et al.* 2007).

In the cluster NGC 6250 proper-motion cluster membership probability and polarization data are available for 33 stars, and only 3 of them have proper-motion membership probabilities greater than 50%. According to the polarimetric study of the cluster NGC 6250, the proper-motion member stars #11 and #35, and non-member stars #13, #18, #19, #37 are probable sources of intrinsic polarization (Feinstein *et al.* 2008).

The above mentioned proper-motion member stars in different clusters are shown in Fig.1, and are probable sources of intrinsic and/or variable polarization. After excluding all these stars from the sample of proper-motion member stars, the scatter is similar to the case when they are included in the clusters NGC 5606, NGC 6231 and NGC 5749. However, the scatter decreases in the clusters Hogg 15, NGC 6611 and NGC 6250. The estimated scatter ($Scatt_a$) and the respective errors of the different clusters after exclusion of stars that are probable sources of intrinsic polarization or produce variable polarization are given in the fifth column of Table 2.

6 POLARIMETRIC CLUSTER MEMBERSHIP PROBABILITY FOR STARS

There are very few open clusters with available interstellar polarization data and a proper-motion cluster membership probability. After an extensive database survey we found six open clusters for analysis. Of these six clusters, two of them, NGC 5749 and NGC 6250, have only three stars with an available proper-motion cluster membership probability. After excluding the stars having probable sources of intrinsic/variable polarization only one proper-motion member star is left in the cluster NGC 6250. So, it is impossible to comment about the scatter $Scatt_a$ in the cluster NGC 6250.

If we assume that the scatter $Scatt_a$ of the Stokes vectors $u(\%)$ and $q(\%)$ depends on the differential intra-cluster reddening $\Delta E(B - V)$, then $Scatt_a$ should increase with increasing $\Delta E(B - V)$. The values of $\Delta E(B - V)$ for all six open clusters are given in the third column of Table 2. Of these six clusters NGC 5749 has the lowest value of $\Delta E(B - V) \sim 0.13$ mag and NGC 6611 has the highest value of $\Delta E(B - V) \sim 0.63$ mag. A $Scatt_a$ versus $\Delta E(B - V)$ plot is shown in Figure 2. The cluster NGC 6250 is not included in the plot because only one member star is left in the sample. It is clear from the plot that $Scatt_a$ increases almost proportionally with $\Delta E(B - V)$ and all the five clusters follow a similar trend. Therefore, the above analysis suggests that the scatter of the Stokes vectors $u(\%)$ and $q(\%)$ of the proper-motion member stars depends on the intra-cluster differential reddening $\Delta E(B - V)$ of different clusters.

The cluster membership probabilities Mp_{prop} , Mp_{pol}^p

and Mp_{pol}^a of different stars belonging to a particular cluster are given in the third, fourth and fifth columns of Table 3 and Table 4. Mp_{prop} is the cluster membership probability based on the proper-motion study given in the third column. Mp_{pol}^p and Mp_{pol}^a are the cluster membership probabilities based on the interstellar polarimetric data given in the fourth and fifth columns. Details about the estimation of the cluster membership probabilities Mp_{pol}^p and Mp_{pol}^a were discussed in Section 3. The estimations of Mp_{pol}^p and Mp_{pol}^a are based on interstellar polarimetric data, though in the case of the estimation of Mp_{pol}^p , the proper-motion cluster membership probability is used as a reference. From Table 3 and 4 it is found that both Mp_{pol}^p and Mp_{pol}^a are comparable, and the cross-correlation coefficient(r) between them is 0.92.

Using a cluster membership criterion (membership probability $> 50\%$ for member stars and $< 50\%$ for non-member stars) we divided the stars into two groups, members and non-members. It is found that for proper-motion member stars both the polarimetric cluster membership probabilities Mp_{pol}^p and Mp_{pol}^a follow the proper-motion cluster membership probability Mp_{prop} , and fall into the same group, *i.e.*, member stars group. The cross-correlation coefficients (r) between Mp_{prop} and Mp_{pol}^p , and Mp_{prop} and Mp_{pol}^a are 0.70 and 0.72, respectively. But for proper motion non-member stars the polarimetric membership probabilities Mp_{pol}^p and Mp_{pol}^a do not follow the proper-motion cluster membership probability Mp_{prop} . The polarimetric cluster membership probabilities Mp_{pol}^p and Mp_{pol}^a should fall in the non-member stars group, but they fall into the opposite group.

Figure 3 shows a comparison between proper-motion and polarization cluster membership probabilities for the stars belonging to the cluster NGC 6231. The left hand side histograms show a comparison between Mp_{prop} and Mp_{pol}^a for the proper-motion member stars, and the right hand side histograms show a comparison for the proper-motion non-member stars. The dotted and lined histograms present the cluster membership probabilities determined by the polarization and proper-motion techniques, respectively. It can be easily inferred from Figure 3 that for the proper-motion member stars, the polarimetric cluster membership probabilities are in good agreement with the proper-motion cluster membership probability whereas for the proper-motion non-member stars the polarimetric cluster membership probabilities totally disagree with the proper-motion cluster membership probability.

7 OPEN CLUSTER NGC 6231

Let us consider the cluster NGC 6231 to study the consistency and validity of the polarimetric membership probability in detail. The reddening $E(B - V)$ and membership probabilities Mp_{prop} , Mp_{pol}^p and Mp_{pol}^a of the different individual stars are given in the second, third, fourth and fifth columns of Table 5. The maximum value of polarization (P_{max}) and wavelength (λ_{max}) are given in the sixth and eighth columns of Table 5. λ_{max} and P_{max} are both functions of the optical properties and characteristics of the particle size distribution of the aligned dust grains (McMillan 1978, Wilking *et al.* 1980). The value of λ_{max} and P_{max}

Table 5. Results for NGC 6231

ID (1)	$E(B - V)$ (mag) (2)	M_{pprop} (%) (3)	M_{pol}^p (%) (4)	M_{pol}^a (%) (5)	$P_{max} \pm \epsilon$ (%) (6)	σ_1 (7)	$\lambda_{max} \pm \epsilon$ (μm) (8)	$\bar{\epsilon}$ (9)
001	0.45	90	82	84	0.846 ± 0.112	1.062	0.553 ± 0.189	18.9
006	0.45	85	88	89	0.355 ± 0.006	0.169	0.615 ± 0.027	10.4
034	0.46	81	68	74	1.511 ± 0.077	0.743	0.656 ± 0.064	12.2
105	0.56	84	84	89	1.175 ± 0.027	0.538	0.493 ± 0.023	2.3
110	0.52	86	94	91	0.476 ± 0.075	0.932	0.427 ± 0.117	6.1
112	0.50	88	94	95	0.549 ± 0.018	0.463	0.536 ± 0.031	4.1
161	0.51	91	75	77	0.441 ± 0.141	1.612	0.321 ± 0.098	1.9
166	0.51	87	69	71	0.699 ± 0.031	0.209	0.439 ± 0.030	2.1
189	0.45	83	87	89	0.558 ± 0.131	0.629	0.377 ± 0.101	3.0
194	0.46	90	95	96	1.018 ± 0.371	0.987	0.205 ± 0.041	2.0
224	0.52	88	92	90	0.345 ± 0.027	0.624	0.507 ± 0.079	6.0
232	0.52	88	89	93	0.911 ± 0.018	0.220	0.484 ± 0.013	2.0
238	0.47	84	93	91	0.407 ± 0.028	0.451	0.549 ± 0.083	7.9
248	0.47	88	66	71	1.614 ± 0.043	0.350	0.468 ± 0.029	9.1
259	0.45	92	86	89	0.891 ± 0.035	0.566	0.472 ± 0.031	1.3
261	0.46	90	92	93	0.588 ± 0.017	0.257	0.450 ± 0.021	1.4
266	0.44	89	77	78	0.396 ± 0.024	0.709	0.589 ± 0.069	5.6
272	0.41	87	88	89	0.592 ± 0.063	0.643	0.382 ± 0.057	5.1
286	0.43	91	78	80	0.533 ± 0.118	0.864	0.348 ± 0.098	8.6
289	0.43	89	71	73	0.731 ± 0.032	0.788	0.439 ± 0.034	0.5
CPD417733	—	91	94	90	0.444 ± 0.034	0.399	0.852 ± 0.095	5.6
016	—	52	89	90	0.371 ± 0.023	0.338	0.542 ± 0.065	2.3
080	0.60	63	72	75	1.036 ± 0.031	0.577	0.551 ± 0.036	8.6
287	0.45	58	66	69	0.830 ± 0.012	0.207	0.474 ± 0.011	0.6
070	0.54	0	61	67	1.616 ± 0.274	5.933	0.627 ± 0.192	367.0
073	0.64	0	81	86	1.953 ± 0.380	7.997	0.725 ± 0.220	199.5
102	0.45	0	90	94	0.847 ± 0.011	0.236	0.581 ± 0.015	16.2
220	0.47	0	85	86	0.657 ± 0.024	0.360	0.506 ± 0.035	14.4
253	0.46	23	86	91	0.985 ± 0.044	0.524	0.480 ± 0.041	7.0
254	0.47	0	95	97	0.928 ± 0.078	0.867	0.460 ± 0.091	33.5
290	0.53	0	85	86	0.666 ± 0.012	0.163	0.469 ± 0.014	6.0
HD152233	—	0	89	90	0.609 ± 0.066	0.926	0.514 ± 0.161	7.4
HD152235	—	0	85	89	1.020 ± 0.021	0.386	0.465 ± 0.015	1.5
HD152248	—	0	80	82	0.562 ± 0.029	0.462	0.533 ± 0.056	6.0

are calculated by fitting the observed interstellar polarization data in U , B , V , R and I band-pass filters using the standard Serkowski's polarization law (Feinstein et al. 2003, Serkowski 1973):

$$P_\lambda / P_{max} = \exp \left[-k \ln^2 (\lambda_{max} / \lambda) \right] \quad (1)$$

and adopting the parameter $K = 1.66 \lambda_{max} \pm 0.01$ (Whittet et al. 1992).

The stars #034, #194, #261 and #253 have a value of $E(B - V) \simeq 0.46$ mag, which is nearly equal to the average value of cluster reddening. The proper-motion cluster membership probability M_{pprop} and polarimetric cluster membership probability M_{pol}^a for these four stars are 81%, 90%, 90% and 23%, and 74%, 96%, 93% and 91%, respectively. M_{pprop} for star #253 is 23% and M_{pol}^a for the same star is 91%. So, according to proper-motion technique, star #253 is a non-member, but according to the polarimetric technique it is a member star of the cluster NGC 6231. The same trend is observed for the remaining proper-motion non-member stars. For example, the stars #70, #73, #102, #220, #254 and #290 have reddening $E(B - V)$ values of 0.54, 0.64, 0.45, 0.47, 0.47 and 0.53 mag. The proper-motion cluster membership probability M_{pprop} for all these stars is 00.0%, but the polarimetric cluster membership probability

M_{pol}^a is 67%, 86%, 94%, 86%, 97% and 86%, respectively. So, it is clear from the above discussions that in the proper-motion non-member regime the methods do not agree. The main reason behind this may be the fundamental differences between the two techniques: M_{pprop} is based on the stellar proper motion in space and M_{pol}^a is based on the interstellar linear polarization, *i.e.*, the selective extinction of star light by aligned asymmetric dust grains present in the interstellar medium along the line of sight.

Since reddening and polarization both originate from similar physical mechanisms, it is expected that the stars #238 and #248 should have the same value of polarimetric cluster membership probability as they both have the same value of reddening $\simeq 0.47$ mag. However, experimentally, this is found to not be the case. We have already stated in Section 2 that the correlation between normal and selective extinction by the asymmetric aligned dust grains cannot be maintained for all cases due to the variations of grain size and alignment efficiency. The entire population of dust grains which are not aligned and elongated may contribute only to reddening and not to polarization. The value of λ_{max} for star #238 is $0.55 \mu m$ and for star #248, it is $0.47 \mu m$. From these values, it is clear that the line of sight for both stars is not populated by grains of similar size, generated

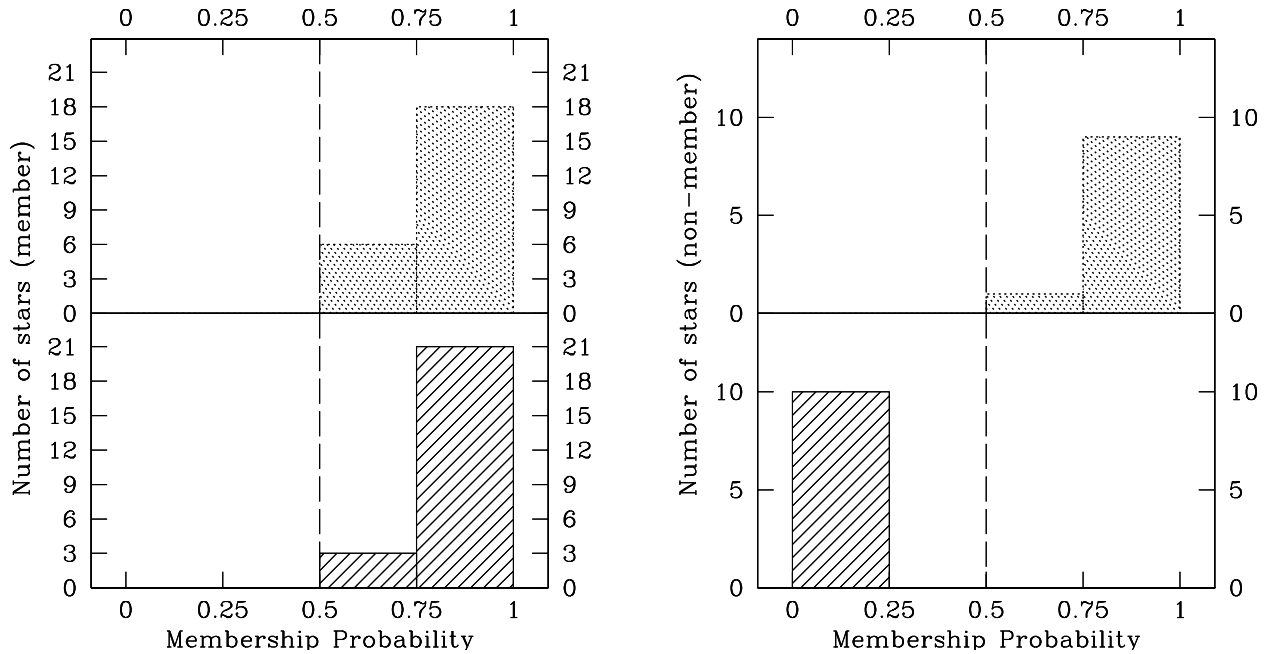


Figure 3. Comparison of cluster membership probability for the stars belonging to the cluster NGC 6231, determined by two different techniques based on proper-motion and interstellar polarization, respectively. The left hand side histogram shows a comparison between the proper-motion and polarization cluster membership probability for the proper-motion member stars and the right hand side histogram shows a comparison for the proper-motion non-member stars. The dotted and lined histograms represent the results determined by the polarization and proper-motion cluster membership techniques, respectively.

by a similar method. Hence, it is possible to have different interstellar linear polarizations as well as different Mp_{pol}^a for different stars even though they all have the same value of reddening.

8 DISCUSSION

From the above results and analysis it is found that our method of estimating the cluster membership probability using linear polarimetric data is applicable only to proper-motion member stars. We can apply this technique to estimate the cluster membership probability for known member stars having no membership probability. However, other techniques are required to eliminate probable non-member stars and stars having sources of intrinsic polarization from the membership sample. Our technique can then be used to determine the cluster membership probability of any star belonging to a particular cluster.

The dispersion of reddening/extinction of a particular star from the mean value of that specific cluster may be used to determine the probable non-member stars in a cluster. Alternatively, the cluster photometry could be used to identify the probable non-member stars in a cluster. Polarimetry is also a very powerful tool for determining stars that have sources of intrinsic polarization. The unit weight error of the fit (σ_1) and dispersion of position angle ($\bar{\epsilon}$) for the stars belonging to cluster NGC 6231 were determined (given in the seventh and ninth column of Table 5). A value of σ_1 , calculated for each star during the fitting of Serkowski's law, of less than 1.5 due to the weighting scheme indicates that the

polarization is well represented by Serkowski's interstellar polarization law (Medhi *et al.* 2010, 2008, 2007). A higher value could be indicative of the presence of intrinsic polarization. The dispersion of the position angle ($\bar{\epsilon}$) for each star normalized by the mean value of the position angle errors is another tool for detecting stars having sources of intrinsic polarization.

We consider seven proper-motion non-member stars from the open cluster NGC 6231 #70, #73, #102, #220, #253, #254 and #290, and assume that proper-motion membership probabilities are not available for all of them. According to the polarimetric cluster membership probability, all of them have a membership probability of $> 50\%$, *i.e.*, all the seven proper-motion non-member stars were identified as being member stars of the cluster NGC 6231. We can use the multi-band linear polarimetric data of the same stars as a supplement to identify whether they are members or non-members. According to a multi-band linear polarimetric study, the dispersion of position angle $\bar{\epsilon}$ for all the seven stars is very high (≥ 6), which implies that they are all probably sources of intrinsic polarization. Therefore, we could easily eliminate them as non-member stars from our sample of polarimetric member stars.

The European Space Agency's space mission Global Astrometric Interferometer for Astrophysics (GAIA) will create an extremely precise three-dimensional map of stars throughout our Milky Way galaxy and beyond. One of the main objectives is to determine the positions, distances and annual proper motions of nearly one billion stars with an expected accuracy of about 7–22 μas down to 15 mag and sub- μas accuracies at the fainter limit of nearly 20 mag (Lin-

degren *et al.* 2007). It is expected that the GAIA will provide very accurate membership information of all stars belongs to open clusters. Once the GAIA data is available, it would provide a much larger sample for cross-checking the polarimetric method.

9 SUMMARY

The findings of the cluster membership study using a polarimetric approach can be summarized as follows.

We have analyzed interstellar polarimetric data for six open clusters, Hogg 15, NGC 6611, NGC 5606, NGC 6231, NGC 5749 and NGC 6250, and estimated the polarimetric cluster membership probabilities for stars belonging to a particular cluster. The analysis suggests that the scatter of the Stokes vectors $q(\%)$ and $u(\%)$ of the proper-motion member stars increases with the highly varying intra-cluster reddening, $\Delta E(B - V)$.

For proper-motion member stars, the polarimetric cluster membership probability Mp_{pol}^a and proper-motion cluster membership probability Mp_{prop} agree. However, for proper-motion non-member stars, the polarimetric cluster membership probability is in total disagreement with the proper-motion cluster membership probability, showing that the polarimetric method is inaccurate for non-member stars. This may be because of fundamental differences between the two methods, in that one is based on the stellar proper-motion in space and other is based on the interstellar polarization, *i.e.*, the selective extinction of the stellar output by the asymmetric aligned dust grains present in the line of sight.

The polarimetric cluster membership determination technique could be used to estimate the cluster membership probability of any star belonging to a particular cluster if we can identify it as a probable member/non-member of that particular cluster using additional polarimetric and photometric information for that star, such as the maximum value of the wavelength λ_{max} , the unit weight error of the fit σ_1 , the dispersion in the polarimetric position angles $\bar{\epsilon}$, the reddening $E(B - V)$ or the differential intra-cluster reddening $\Delta E(B - V)$. This technique could also be used to estimate the cluster membership probability for the known member stars with unknown membership probability as well as to resolve disagreements about membership between different proper-motion surveys (Dias *et al.* 2006, Baumgardt *et al.* 2000, Belikov *et al.* 1999, Tucholke *et al.* 1986, Berger 1982).

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